Title

Restricting ankle motion via orthotic bracing reduces toe clearance when walking over obstacles

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- We report effects of lead-limb ankle restriction on obstacle crossing
- Ankle restriction caused a shift in foot placement before and after the obstacle
- Hence point of crossing occurred later in swing, which led to reduced clearance
- Findings highlight that ankle bracing/arthrodesis compromises adaptive gait safety

Abstract

Background: When trans-tibial amputees cross obstacles leading with their prosthesis, foot clearance is achieved using compensatory swing-phase kinematics. Such compensation would suggest able-bodied individuals normally use swing-phase ankle dorsiflexion to attain adequate obstacle clearance, however, direct evidence of such contribution is equivocal. The present study determined the contribution of sagittal plane ankle motion in achieving lead-limb clearance during obstacle negotiation.

Methods: 12 male able-bodied individuals (ages 18-30) completed obstacle crossing trials while walking on a flat surface. Lead-limb (right) ankle motion was manipulated using a knee-ankle-foot orthosis. Trials were completed with the ankle restricted at a neutral angle or unrestricted (allowing ~ ±15 ° plantar/dorsiflexion).

Findings: Restricted ankle motion caused significant increase in trail-limb foot placement distance before the obstacle ($p=0.005$); significant decrease in vertical toe clearance ($p<0.003$), vertical heel clearance ($p=0.045$) and lead-limb foot placement distance after the obstacle ($p=0.045$); but no significant changes in knee angle at instant of crossing or in average walking speed.

Interpretation: The shifts in foot placements altered the part of swing that the lead-limb was in when the foot crossed the obstacle, which led to a decrease in clearance. These adaptations may have been due to being unable to dorsiflex the ankle to 'lift' the toes in mid-swing or to being unable to plantarflex the ankle during initial contact following crossing, which changed how the lead-limb was to be loaded. These findings suggest individuals using ankle bracing or those with ankle arthrodesis, will have reduced gait safety when negotiating obstacles.

Key Words

orthotics; ankle; foot clearance; obstacle crossing, gait

1. Introduction

Compared to locomotion on flat ground, obstacle crossing requires significant adaptations to gait to ensure that foot clearance over the obstacle occurs with sufficient margins of safety [1-4]. Tripping on obstacles is a key cause of falls in the elderly [5-6]. The risk of tripping and/or the ability to prevent a trip from becoming a fall has been shown to be affected by several factors. These are the speed of the swinging foot [2], response time [7], alterations in stance-limb kinematics and kinetics [8], changes in foot placement distance before and after the obstacle [9], and age and/or the physical competency of the individual [10-13].

Much of the research on obstacle crossing has highlighted the importance of swing-limb hip and knee flexion and pelvic obliquity in achieving clearance [2, 3, 14]. When there is a loss of ankle motion, for example as in the case of trans-tibial amputees, hip-hiking and increased knee flexion are adaptations used to maintain clearance [15,16]. However, the importance of swing phase ankle motion itself in achieving clearance has not been directly researched. Instead it is often simply mentioned that ankle dorsiflexion during swing assists the proximal joints in attaining/increasing clearance [2-4,14,17].

Although, compared to the hip and knee, the range of motion of the ankle is relatively small, a few degrees of dorsiflexion during swing will lift the toes by 1 to 5 cm [18]. For locomotion on flat ground where toe clearance is smallest during mid-swing, it has been suggested that ankle dorsiflexion is more effective at raising the toe than either knee or hip flexion [8], thereby potentially contributing significantly to attaining appropriate margins of safety. However, whether such dorsiflexion is routinely adopted during obstacle crossing is presently unclear.

The aim of the present study was to directly assess the contribution of swing phase ankle motion in achieving lead-limb obstacle clearance while crossing obstacles of different heights. Specifically, we determined whether there were any significant changes in foot placements and clearance and swing-phase knee flexion when ankle (but not knee) motion was restricted using a knee-ankle-foot orthosis (KAFO). The hypothesis was that the restriction of lead-limb ankle motion would cause no significant change in obstacle clearance due to a compensatory increase in swing-phase knee flexion, and that such minimal effects on gait would mean there would be no changes in foot placement distances before or after the obstacle.

2. Methodology

Twelve able-bodied male adults (age 18-30 years, mass 76±12 kg, height 181±6.3 cm) without history of musculoskeletal pathology or trauma to either the lower-limbs or back, and of self-reported medium activity level, volunteered to take part in this study. All volunteers gave written informed consent, and ethical approval was obtained from the institutional ethics committee.

A KAFO was attached and adjusted to each participant's right limb while the participant was standing upright and stationary. The bilateral side-steels with knee and ankle hinges limited knee and ankle motion to the sagittal plane. The ankle hinges could be restricted by 'screwing down' two grub screws positioned anterior and posterior of each hinge centre (Figure 1). This permitted two ankle conditions: 1) *restricted* at a neutral angle (0 ° plantar/dorsiflexion), and 2) *unrestricted* for free sagittal plane motion (up to ±15 ° plantar/dorsiflexion). The KAFO was adjusted so that the *restricted* position represented the neutral standing ankle angle. The length of the KAFO's shank section side-steels were adjusted to ensure the bilateral mechanical knee hinges (freely articulating) were centred as close as possible to each participant's anatomic knee axis. Distally, the KAFO was attached via its bilateral rectangular spurs to corresponding rectangular sockets in the heel of customised shoes (Figure 1). Shoes (all same model) were of UK sizes 8-11, and thus only those participants who habitually wore shoes of these sizes were recruited. The positioning of the heel sockets in each pair of shoes ensured the bilateral mechanical ankle hinges would be centred as close as possible to participants' anatomic ankle axis. Proximally, the KAFO was secured with Velcro straps around the thigh and shank.

Use of an adjustable KAFO was preferred over using an AFO for pragmatic reasons. That is, a KAFO's thigh straps would limit anterior-posterior movement of the shank section side-steels and hence the shank strap, and thus restrict ankle motion (when in restricted mode), to an extent that would have otherwise required a bespoke custom moulded AFO for each participant to achieve.

Participants were given time to familiarise themselves with the two ankle conditions while walking freely around the laboratory's level surface for approximately five minutes. Participants walked at a freely chosen speed along a straight and level walkway and crossed over an obstacle placed half way along the walkway. Participants were asked to cross the obstacle leading with the limb the KAFO was fitted to and were reminded of this after approximately every 4 trials. Obstacles of four different heights (3, 7, 11.5, and 15 cm) were negotiated four times each. The obstacles were made of 3 mm thick hardboard secured to wooden triangular shaped feet and would fall forward if contacted (Figure 2). Kinematic data were collected at 100 Hz using an 8-camera motion capture system (Vicon Workstation, Oxford, UK). Each participant wore 22 reflective markers placed on/over the following locations: each shoe over end of the 2nd toe, 2nd and 5th metatarsal heads, and posterior aspect of calcaneus; each limb on lateral malleolus, lateral femoral condyle (NB, on right limb these were placed on the KAFO), and lateral aspect of the shank and thigh; and on the left and right ASIS and sacrum, the sternum, and either side of the top edge of the obstacle. A static 'subject calibration' trial was captured for each participant.

Trials were completed in two blocks: *restricted* ankle and *unrestricted* ankle, with block order counterbalanced across participants. Hence, participants completed a total of 32 obstacle crossing trials (2 ankle conditions × 4 obstacle heights per ankle condition × 4 obstacle crossings per obstacle height). For each block, the different obstacle heights and repetitions where completed in random order.

Starting position was two average walking steps away from the obstacle. Starting location was the distance from the obstacle that allowed participants to cross over it with the right (KAFO) limb without any observable change in step length. This location was randomly varied by ±3 cm in an attempt to discourage participants from completing each trial in a mechanistic manner. After testing the first ankle condition, participants stood stationary whilst the ankle condition was changed (by screwing in/out grub screws). Seated rest was also offered but mostly declined.

Marker trajectory data were labelled and gap filled using Plug-In-Gait software (Oxford Metrics, Oxford, UK). Data were then filtered using the Woltering routine with a Mean Square Error (MSE) of 10, and a 3D link-segment lower body model was defined for each participant (based on the Helen Hayes marker set, Oxford Metrics). 3D coordinate data of the markers on each foot, the obstacle and the sternum, along with knee angular displacement data were subsequently exported in ASCII format for further analysis. All outcome measures were determined from the ASCII file for each trial, using 'in-house' analyses routines written in Visual Basic.

Obstacle clearance has been reported as the distance between the obstacle and the toe or the obstacle and the heel, as these parts of the foot are nearest to the obstacle during crossing [4, 13, 19-21]. For this reason, the current study takes both clearances into consideration as well as foot placement parameters (i.e. distances relative to the obstacle) to quantify how gait was adapted when lead-limb ankle motion was restricted. The parameters analysed are shown in Table 1 and depicted in figure 2.

Kolmogorov-Smirnov normality tests determined data were normally distributed. Hence data were analysed using repeated measures (2 x 4) ANOVAs to determine main and interaction effects of ankle condition (*restricted*, *unrestricted*) and obstacle height on all gait parameters. The alpha level was set at $p<0.05$. Post hoc analyses were performed using Tukey (HSD). Statistical analyses were performed using STATISTICA software (StatSoft Ltd, Bedford UK).

3. Results

Figure 3 presents mean and SD VTC for the restricted and unrestricted ankle conditions across the four obstacle heights, and Table 2 shows mean and SD of all other spatio-temporal gait parameters analysed. VTC was lower in the restricted compared to unrestricted ankle condition ($p<0.003$) and increased with increasing obstacle height ($p<0.001$). A significant interaction between terms ($p<0.045$) indicated the increase in VTC with increasing obstacle height was reduced for the restricted compared to unrestricted ankle condition.

VHC was lower for the restricted compared to unrestricted ankle condition (trend, p=0.057) and increased with increasing obstacle height (p<0.001). A significant interaction between terms (p=0.01) indicated that the increase in VHC with increasing obstacle height was reduced for the restricted compared to unrestricted ankle condition.

Trail-1 was greater for the restricted compared to unrestricted ankle condition (by on average 3.6 cm, p=0.005) and increased with increasing obstacle height (p<0.001); there was no interaction between terms (p=0.21). Lead-1 was unaffected by ankle condition (p=0.115) but increased with obstacle height (p=0.02); there was no interaction between terms (p=0.32). Lead+1 was reduced for the restricted compared to unrestricted ankle condition (average 2.3 cm, p=0.045) but was unaffected by obstacle height (p=0.79); there was no interaction between terms (p=0.47). Knee angle at instant of crossing was unaffected by ankle condition (p=0.66) but increased with increasing obstacle height (0.006); there was no interaction between terms (p=0.50). Average crossing walking speed was unaffected by ankle condition (p=0.095) but decreased with increasing obstacle height (p=0.003); there was no interaction between terms (p=0.79).

4. Discussion

The present study investigated the importance of lead-limb ankle motion in attaining foot clearance when crossing obstacles. Findings indicate that restriction of lead-limb ankle motion via orthotic bracing led to a significant decrease in foot clearance. Restricted ankle motion also led to a change in foot placement distance before and after the obstacle, which altered the part of swing that the lead limb was in when the foot crossed the obstacle, which, because there was no compensatory increase in knee flexion, led to the decreased clearance. The likely cause(s) of these adaptations are discussed below. The results show that ankle motion typically contributes to attaining foot clearance when crossing obstacles.

The increase in Trail-1 distance and reduction in Lead+1 for the restricted ankle condition (hence no change in crossing step length), indicates that, with an inability to dorsiflex the ankle to 'lift' the toes during swing, participants altered the placement of their feet relative to the obstacle to change the lead-limb foot trajectory over the obstacle. However, given that this alteration caused a (seemingly maladaptive) reduction in toe and heel clearance, it must have been driven by factors other than solely achieving clearance. One possible factor is how the limb would be loaded following crossing. It has recently been demonstrated that when unilateral trans-tibial amputees cross obstacles they use different gait adaptations compared to able-bodied controls (when leading with their prosthetic limb) [19]; seemingly related to a desire to attain a limb/foot angle at the instant of landing that minimises loads on the residuum [19]. In the present study, the restriction of lead-limb ankle motion would have altered participants' ability to attenuate the ground reaction forces for the step immediately following crossing. An inability to attenuate the ground reaction forces in the restricted ankle condition would have been due to not being able to plantarflex the foot to lower it to the ground following initial contact. This would have delayed and/or changed how a 'foot flat' position was achieved and hence delayed and/or changed knee flexion limb-loading response. Hence, the altered foot placement and crossing step foot trajectory may have occurred to achieve a limb/foot angle at the instant of contact that ensured the lead/involved limb was loaded within safe/comfortable limits. Not being able to plantarflex the foot following initial contact would potentially also affect dynamic balance control during weight acceptance, and thus the change in limb/foot angle at instant of contact may have also been partly due to a desire to maintain dynamic balance parameters within margins of safety.

With an increase in support/trailing limb foot placement distance before the obstacle, the lead-limb would have been in a more outstretched position in front of the individual during the period when the foot crossed over the obstacle. A more outstretched limb at point of crossing indicates the limb was in a later part of swing phase. This means that, when the ankle was restricted, participants crossed over the obstacle with their lead-limb in a later part of its swing phase compared to that for the unrestricted ankle condition (where instant of lead-limb crossing occurred closer to mid-swing). With the limb in the later part of swing, the heel crossed over the obstacle whilst the foot was on the descending part of its trajectory. This suggests that the instant when the heel cleared the obstacle would have been a more important event in the restricted compared to unrestricted ankle condition.

Previous research has demonstrated that older adults attempt to cross over obstacles in the later part of swing because contact with the obstacle later in swing is less likely to cause a trip in comparison to contact early on in swing due to the relatively more posterior position of the body centre of mass in late swing [4]. The authors noted that, although this strategy resulted in higher toe-clearance the trade-off was reduced heel clearance [4]. Other research has highlighted that, when crossing obstacles leading with their prosthesis, unilateral trans-tibial amputees (with no ability to alter prosthetic 'ankle' angle) attend more to how their heel crosses the obstacle compared to able-bodied controls [19]. In the present study, heel clearance became significantly increased for both ankle conditions as obstacle height increased, but such increases were significantly reduced for the restricted ankle condition (heel clearance increases *unrestricted*, ~1.6 cm; *restricted*, ~2.7 cm). The reduced heel clearance for the restricted ankle condition would have been due to the lead-limb being in a later part of swing phase and hence more outstretched at point of crossing. Following the instant the heel crosses over the obstacle, it would be desirable, when the limb is outstretched, for the foot to be placed on the ground as quickly as possible. This likely explains why heel clearance did not increase with obstacle height increases as much as was the case for the unrestricted ankle condition, because such increases would counter the ability to place the foot on the ground as quickly as possible.

Average crossing walking speed was found to decrease approximately linearly with increasing obstacle height for both ankle conditions, possibly because either greater caution was required to successfully cross the higher obstacles, which is in accordance with Chou, Draganich and Song [1], or because crossing the higher obstacles required higher limb elevation, which reduced forward propulsion. There was also a trend ($p=0.095$) towards a reduction in average crossing speed for the restricted ankle condition, and this was likely because restriction of the ankle reduced the amount of late stance ankle power on the involved side, which is known to be related to forward propulsion [19]. This reduction in crossing speed as a result of ankle restriction corroborates previous research, indicating that individuals with trans-tibial or those who had undergone ankle arthrodesis amputation have reduced walking speed compared to healthy controls [22, 23].

4.1. Limitations

Adjusting the length of the KAFO's shank section side-steels was limited to set increments, which meant only reasonable precision was possible while trying to align the bilateral mechanical knee hinges with each participant's anatomic knee centre. However, the increments were 10 mm apart, and hence misalignment was less than 5 mm and therefore not considered detrimental. The use of a KAFO (with freely articulating knee hinges) may have caused some degree of restriction at the knee joint due to misalignment of the single axis hinges and the anatomic knee's polycentric axis, and/or due to limiting knee motion to only the sagittal plane. However, findings indicate the knee flexion angle at the instant of crossing increased with obstacle height with no difference between the restricted and unrestricted ankle conditions, which suggests that the freely articulating knee hinges (limiting knee motion to only the sagittal plane) had little or no impact on the results presented.

Hip motion was not investigated in the current study, because we believed that any compensatory change in hip angle would coincide with (and thus be reflected by) a similar change in knee angle (due to the kinematic coupling between these two joints). Since foot clearances decreased when ankle motion was restricted, and there was no compensatory increase in the amount of knee flexion at crossing, it is unlikely there would have been any significant change in the hip flexion angle at crossing as a result of the ankle motion restriction.

5. Conclusion

The current study has identified the importance of lead-limb ankle motion in attaining foot clearance during obstacle crossing. Restriction of lead-limb ankle motion caused compensatory shifts in foot placement distances before and after the obstacle, yet no change in crossing step length (suggesting no fundamental change in gait). As a result, this altered the part of swing that the lead-limb was in when the foot crossed the obstacle, which led to a decrease in foot clearance. These adaptations may have been a consequence of being unable to dorsiflex the foot to 'lift' the toes in mid-swing or because of a change in how the lead-limb was loaded during initial contact following crossing (due to ankle's inability to plantarflex). These findings suggest that elderly individuals with reduced ankle range of motion or ankle arthrodesis will have reduced gait safety when negotiating obstacles. However, in individuals using certain types of AFO to prevent drop foot, the orthosis is often key to maintaining clearance. Therefore our findings cannot be used to argue against using AFOs in these individuals because their lack of use could have more detrimental effects on foot clearance.

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Figure 1. KAFO used to restrict ankle motion. In the restricted condition, two grub screws on each side of the ankle hinge (circled in white) restricted the ankle to a neutral angle: see text for further details.

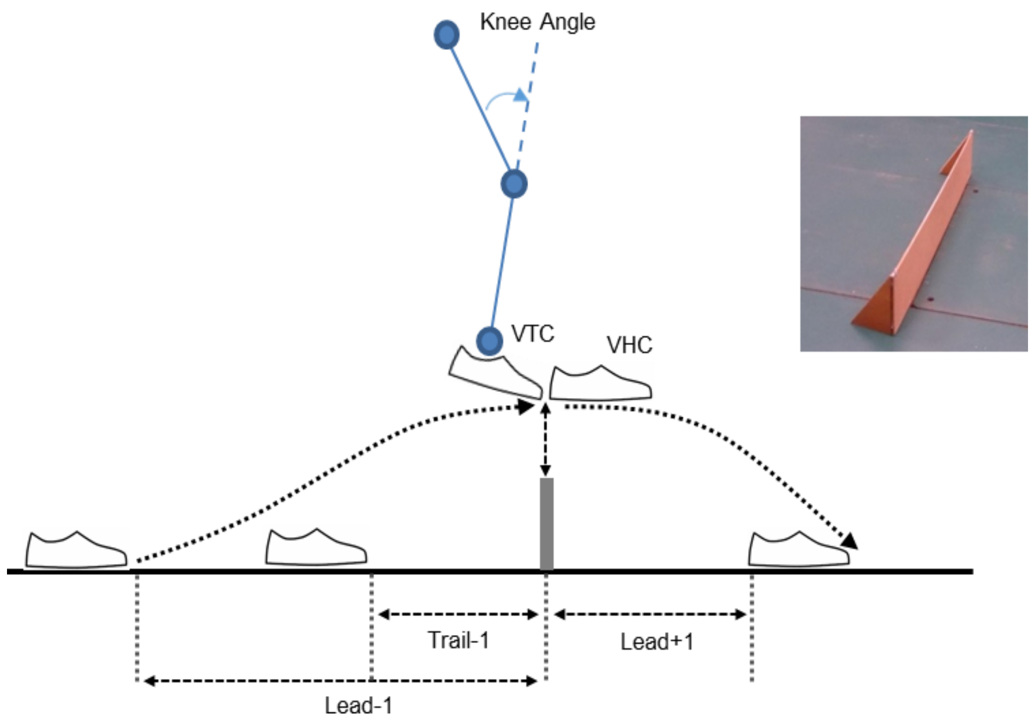

Figure 2. Schematic of the variables analysed: VTC – vertical toe clearance, VHC – vertical heel clearance, Trail-1 – horizontal distance between trail foot toe and obstacle, Lead+1 – horizontal distance between lead foot heel and obstacle, Lead -1 – horizontal distance between lead foot toe and obstacle before foot crossing, and Knee Angle – sagittal plane angle between the thigh and shank segment at the instant of VTC. Inset shows the medium height (7 cm) obstacle; the obstacle would easily fall forwards if contacted (when walking from left to right direction).

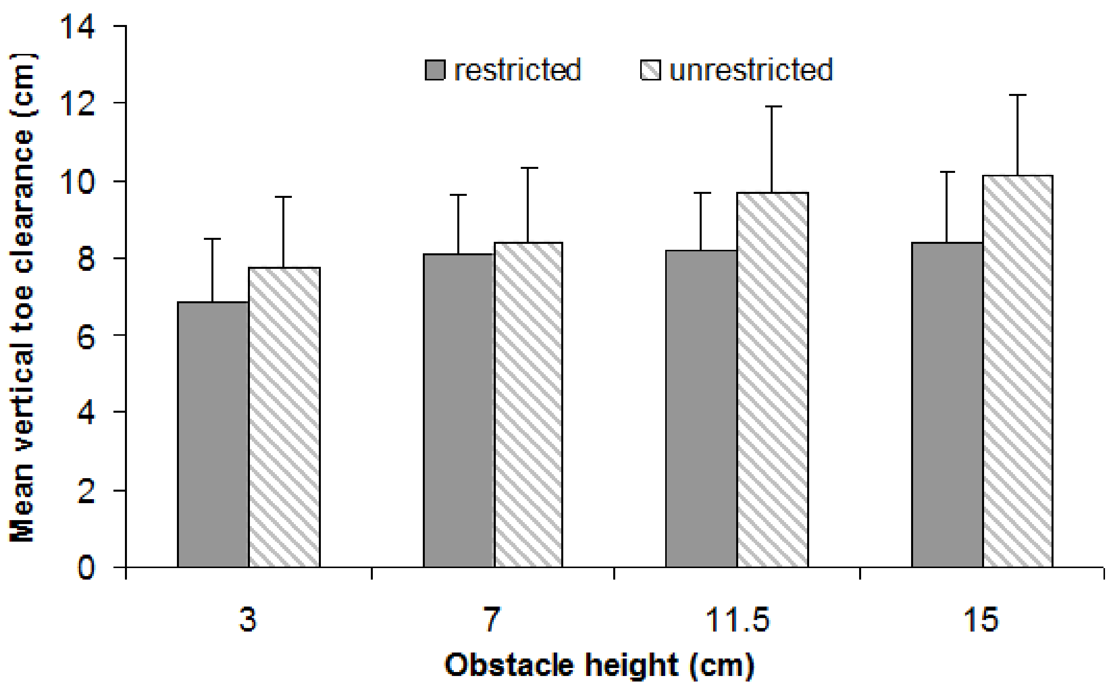

Figure 3. Group mean ± SD Vertical Toe Clearance (VTC) for restricted and unrestricted ankle conditions across all four obstacle heights.

Table 1: Outcome measures and their definition.

Lead limb vertical toe clearance (VTC) and vertical heel clearance (VHC):

- the vertical distance between the lead limb 2nd toe and calcaneus marker and the obstacle at the instant when the lead limb toe and calcaneus marker, respectively, were directly above the obstacle

Trail and lead limb foot placement distance before the obstacle (Trail-1, Lead-1):

- the horizontal distances between the trail and lead limb 2nd toe marker and the obstacle

Lead limb foot placement distance after the obstacle (Lead+1):

- the horizontal distance between the lead limb calcaneus marker and the obstacle

Lead limb knee angle at instant of crossing:

- the sagittal plane angle between the thigh and shank segment at the instant of VTC

Average walking crossing speed during crossing:

- the average anterior-posterior velocity of the sternum marker for the period from 0.5 seconds before to 0.5 seconds after the instant of VTC

Table 2. Group mean & SD spatio-temporal parameters and knee angles for the unrestricted (unR) and restricted (Res) ankle conditions when crossing each obstacle height.

		3 cm	7 cm	11.5 cm	15 cm	
VHC (cm)	unR	7.2 (3.6)	8.3 (2.3)	9.5 (2.9)	9.9 (2.3)	Orth ***(p<0.001)*** ES, 0.34
	Res	7.0 (2.0)	8.0 (1.5)	8.4 (1.9)	8.6 (2.1)	Ht (p=0.057) Int (p=0.01)
Lead-1 (cm)	unR	39.5 (7.3)	39.4 (7.3)	39.9 (9.9)	40.9 (8.7)	Orth (p=0.115) ES, 0.26
	Res	38.9 (4.1)	42.2 (8.2)	2.9 (6.0)	43.4 (5.9)	Ht ***(p=0.02)*** Int (p=0.32)
Trail-1 (cm)	unR	23.6 (1.7)	24.3 (1.7)	24.9 (2.2)	24.5 (11.9)	Orth ***(p=0.0005)*** ES, 0.61
	Res	24.3 (1.9)	25.8 (2.0)	25.5 (1.7)	26.3 (11.9)	Ht ***(p=0.0003)*** Int (p=0.21)
Lead+1 (cm)	unR	17.8 (4.9)	17.1 (3.7)	17.0 (4.4)	17.5 (4.2)	Orth ***(p=0.045)*** ES, 0.49
	Res	15.3 (4.8)	15.0 (5.5)	15.6 (5.0)	14.3 (4.6)	Ht (p=0.79) Int (p=0.47)
Knee angle at crossing (deg)	unR	23 (9)	26 (11)	27 (11)	26 (11)	Orth (p=0.66) ES, 0.04
	Res	23 (8)	25 (8)	26 (10)	26 (10)	Ht ***(p=0.006)*** Int (p=0.50)
Crossing walking speed (cm/s)	unR	50 (13)	48 (13)	46 (14)	44 (15)	Orth (p=0.095) ES, 0.39
	Res	46 (11)	44 (12)	43 (15)	41 (13)	Ht ***(p=0.0003)*** Int (p=0.79)

Orth = ankle condition effect; ES = ankle condition effect size; Ht = obstacle height effect; Int = ankle condition-by-obstacle height interaction effect; significant differences are highlighted in ***bold italics***.